KNOWLEDGE REUSE FOR INNOVATION – THE MISSING FOCUS IN KNOWLEDGE MANAGEMENT: RESULTS OF A CASE ANALYSIS AT THE JET PROPULSION LABORATORY

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Abstract –

Research on knowledge management focuses on the capture, transfer, and reuse of knowledge. In this paper, we make a distinction between the reuse of knowledge for routine tasks (e.g., use of templates, boilerplates, and existing solutions) versus reuse that stimulates knowledge synthesis and innovation (e.g., searching a database to find new ideas to combine with existing knowledge). We argue that very little research has focused on the latter type of reuse and as a result leave questionable the extent to which we know how to facilitate reuse for innovation. We describe the results of six case analyses of reuse for innovation at the Jet Propulsion Laboratory. From this research, we have derived a model that identifies eight factors likely to encourage knowledge reuse. From these eight factors we have synthesized four generalizable factor categories in a variance model. In addition, our research yields a process model that helps to explain how the eight factors influence knowledge reuse, and how the reuse process unfolds in an innovation context. Implications of these two models for research and practice are presented.

Keywords: Knowledge reuse, Knowledge Management, innovation

How organizations create, retain, transfer and reuse knowledge has been a subject of increasing interest to organizations in recent years (Argote, 1999; Argote, Ingram, Levine, & Moreland, 2000; Huber, 1991). Strategic considerations that tie the transfer of knowledge to strategic necessity have fueled the fire. Under the environment of globalized capitalism, firms require the effective transfer and use of knowledge in order to function effectively (Drucker, 1991, Ch. 1; Giddens, 1991, Ch. 1; Reich, 1991, Ch. 7-10). It has been theorized that firms that effectively transfer knowledge, while preventing competitors from tapping into their knowledge resources, are more successful than those that do not effectively manage their knowledge resources (Lippman & Rumelt, 1982; Winter, 1995; Zander & Kogut, 1995).

This recognition of the importance of knowledge transfer to a firm has led to the development of knowledge management systems (KMS) intended to enhance the knowledge transfer process. KMS are defined as

> "information systems designed specifically to facilitate codification, collection, integration, and dissemination of organizational knowledge." (Alavi & Leidner, 1999: 4)

A typical knowledge management system involves a data (or knowledge) base, a cataloguing system, version control, document access control, a user-friendly search and navigation capability, and a possible variety of advanced features such as email notification or commenting. Because KMS involve the cataloguing of knowledge for later reuse, most KMS today have been developed to enhance the efficiency of a work process (Davenport, Jarvenpaa, & Beers, 1996; Todd & Benbasat, 2000). As such, documents are captured and catalogued to support likely known future reuses, such as consultant services or administrative templates (Davenport et al., 1996). Ernie is an example of such KMS in which consultants use keyword and advanced Boolean searches to identify solutions used previously for clients with similar problems.

KMS need not only be used to support process efficiency, however. Since knowledge transfer is a critical part of innovation (Darr & Kurtzberg, 2000; Pennings & Harianto, 1992) both within and across firms (Garud & Nayyar, 1994; Gilbert & Cordey-Hayes, 1996; Szulanski, 1996), KMS should be able to be designed to support knowledge transfer for innovation, not just for routine reuse. But knowledge transfer for innovation takes a different form than knowledge transfer for routine reuse. Innovation, by definition, means the use of knowledge in unknown future contexts and thus simple searches of any repository are unlikely to yield innovative outcomes. Moreover, innovation involves the questioning of implicit assumptions, constraints, and principles of the knowledge as it was used in one context to determine the extent to which the knowledge can be applied (or recontextualized) to an alternative context (Burdett, 1993; Coopey, Keegan, & Emler, 1998; Garud, Nayyar, & Shapira, 1997; Majchrzak & Beath, 2001). Thus, knowledge transfer for innovation requires not simply a repository and search engine, but a way to organize, represent, and query knowledge to elicit implicit assumptions and recontextualized knowledge.

Typically, this process of organizing and querying knowledge for innovation is performed exclusively by humans (sometimes with the aid of a coordination tool) in hallway discussions, phone meetings, or formal brainstorming sessions, with little formal aid of KMS (Davenport et al., 1996; Markus, 2000). For example, Shneiderman (1998) lamented that software tools have had little success in supporting creative problem-solving, Vandenbosch and Huff (1997) found few uses of executive information systems for creative work, and Kivijarvi and Zmud (1993) hypothesized that information systems structured to facilitate decision-making would not be successful in domains characterized by creativity. Therefore, KMS that organize, represent, and provide ways to elicit recontextualized assumptions for innovation are still in their infancy.

Before such KMS for innovation can be developed, we must have a much clearer understanding of how knowledge is transferred within an innovation context so that suggestions for such KMS and their use can be better targeted. Does knowledge transfer in innovation proceed exclusively as unexplicated tacit knowledge or can knowledge be structured systematically for innovative use? Is there a set of critical factors that influence knowledge transfer for innovation that can be designed into a complete sociotechnical knowledge management solution? These are the questions this paper is intended to address. First we review the literature on existing theories of knowledge transfer to generate possible factors that might enable knowledge transfer for innovation, rather than for routine reuse. Then, we present the results of an exploratory six-case analysis of knowledge transfer in innovation to empirically ground these factors in actual innovative knowledge transfer situations. From this research process, we conclude by identifying eight factors that are hypothesized to constitute minimal requirements for KMS for innovation.

I. REVIEW OF LITERATURE ON KNOWLEDGE TRANSFER

Knowledge has been defined in a variety of ways. Based upon the work of Nonaka (1994), Huber (1991) and Alavi (1999), "Knowledge is (defined as) justified personal belief that increases an individual's capacity to take effective action." (Alavi et al., 1999: 4). There has been a multitude of research on knowledge management that has yielded factors that affect knowledge transfer. We have classified this research into four streams:

1. Knowledge creation and knowledge management models
2. Common ground
3. Organizational learning
4. Resource based view: knowledge capital as an organizational asset

Knowledge Creation and Knowledge Management Models

Knowledge creation models have been concerned with how tacit and explicit knowledge from individuals, groups, and entire organizational entities are combined to generate process, product and technological innovation (Kogut & Zander, 1992). Underlying this model has been the debate concerning the sharp or blurred distinction between tacit and explicit components of knowledge. Nonaka and Takeuchi (1995) and Spender (1996) separate the tacit and explicit components of knowledge. Spender (1996) suggested a 'pluralistic epistemology' that captures a further segmentation of the different types of knowledge into explicitly articulated knowledge and implicitly manifested knowledge.

Using these distinctions, a view of knowledge transfer has been promoted that involves transforming tacit to explicit knowledge. (Hedlund, 1994; Kogut et al., 1992; Sherman & Lacey, 1999). For example, Nonaka and Takeuchi (1995) propose a four-stage knowledge creation (i.e., transfer) model that includes socialization, articulation, combination, and internalization. These stages present formalized communication structures and teambuilding interventions as the mechanisms for transfer, capture, and making tacit knowledge explicit (Bresman, Birkinshaw, & Nobel, 1999; Sherman et al., 1999). Von Krogh, Ichijo and Nonaka (2000) describe five other mechanisms: instill a vision, manage conversations, mobilize knowledge activists, create the right context, and globalize local knowledge.

In contrast to the model of knowledge transfer in which tacit knowledge must be made explicit, Polanyi (1966) favors a blurred distinction between tacit and explicit knowledge, noting that there is a tacit component to all knowledge (Kogut et al., 1992; Teece, 1981). Tacit knowledge is often held sub-consciously until it is used (Reed & deFillippi, 1990). Tsoukas (1996) asserts that articulated knowledge is based upon an unarticulated background including social practices that are internalized and cognitive in nature. In an organization, the culture, routines, stories and the "invisible assets" of the organization are common repositories for tacit knowledge (Harris, 1994; Itami, 1987; Nelson & Winter, 1982; Ouchi, 1980).

From this perspective, the knowledge transfer process occurs through the ability of an organization to combine both tacit and explicit knowledge. The knowledge transfer process, then, is not one of making knowledge codified and explicit, but is one of sharing stories and interpretations so that new tacit knowledge for new contexts is combined with existing tacit knowledge. Thus, the distinction between tacit and explicit knowledge becomes less important for knowledge transfer than how knowledge is combined (Brown & Duguid, 1998). Knowledge transfer can be described as a process where knowledge is recombined from both "inward" and "outward" sources (Kogut et al., 1992). Kogut and Zander (1992) note a circular connection between exploitation (use of internal knowledge) and exploration (invention, outward search).

For innovative reuse of knowledge, we believe that the knowledge that is transferred is more likely to be characterized by a blurred distinction between tacit and explicit knowledge, as proposed by Polanyi, (1966). Thus, a minimum requirement of KMS for innovation is to not separate out explicit knowledge (for the repository) from tacit knowledge (for the hallway conversations) but allow descriptions of both types of knowledge. However, this does not invalidate Nonaka's suggestions. KMS may also need to allow sharing knowledge for globalizing local use; and allow knowledge reusers to experiment with different combinations of knowledge from both internal and external sources.

Common Ground

Clark and Brennan’s (1993) and Clark’s (1996) theory of language use suggests that veridicality of communication is more likely when both parties to the communication have a "common ground". Common ground can be defined as the beliefs, knowledge and suppositions that the parties believe they share about the joint activity. In this theory, common ground is developed through interactions and communication that include requests, promises, assertions, questions, apologies, declarations, and responses. Recent research has confirmed, the greater the common ground between the knowledge reuser and the knowledge contributor, the more likely that reuse will occur for innovative problems (Majchrzak, Rice, Malhotra, King, & Ba, 2000).

Common ground can be facilitated in a variety of different ways. While some authors suggest that common ground is primarily created through in-person interactions (Clark & Brennan, 1991; McGrath & Hollingshead, 1993; McGrath & Berdahl, 1998), Olson and Olson (1998) have identified ways in which common ground can be created electronically, through the use of shared artifacts such as common stories or myths, shared documents, or shared metaphors (Brown et al., 1998). While Brown & Duguid (1998), Hutchins (1991), and Olson and Olson (1998) limited their discourse on shared artifacts to those artifacts that are shared among a single community of practice, it is possible to conceive of a situation in which shared artifacts could be used to transfer knowledge across different communities of practice. For example, a meteorologist may use a basic physics principle as the shared artifact to understand and evaluate the contribution of a structural engineer.

In the innovation context, common ground can be defined by the mutual understanding of the project objectives and goals, technical and organizational constraints, and appropriate analytic processes for problem solving. In addition, common ground can be conceptualized as the set of shared norms, defined as the expectations for how people should behave (Ouchi, 1980; Tsoukas, 1996). In the knowledge transfer and reuse context, critical norms have been found to include who has access to what knowledge, how is the quality of the knowledge evaluated, and what attributes of the knowledge should be captured for later use (Davenport & Prusak, 1998; Majchrzak et al., 2000).

This stream of research then suggests that, for a knowledge transfer process focused on generating innovation, the process of knowledge transfer should convey, and encourage the development of, a common ground between knowledge contributors and potential knowledge reusers. In a single community of practice, such common ground might be assumed. However, when the innovation crosses communities (as it should for revolutionary innovation to occur), KMS should facilitate the development of a common ground. Facilitation can be accomplished, first, by encouraging knowledge contributors to share their assumptions about such common ground issues as project objectives, constraints, problem-solving processes, and knowledge acquisition, evaluation, and use norms. Then, KMS should help knowledge reusers to translate these assumptions into their own contexts through the interactive creation of shared artifacts, such as by contributing to stories, metaphorical analyses, question-and-answer sessions, or evaluation matrices.

Organizational Learning

According to Weick (1995), organizational learning involves openness to the notion that different people may have different views on the reality of the same fact. This openness may create a great deal of ambiguity, but it is necessary to accept ambiguity in order to achieve innovation. A variety of interpretations may lead to additional learning opportunities (Huber, 1991). Senge (1990) elaborates on how to encourage this openness in the organizational learning process. He suggests five types of behaviors: systems thinking, clarifying personal visions, shifting mental models, building a shared vision, and engaging the team in joint and open dialogue (Senge, 1990). Interpretations of information are dependent upon the way individuals diverge and converge in relation to the mental models of the group (Ireland, Hitt, Bettis, & DePorras, 1987; Walker, 1985). In addition, the way information is framed will affect its shared meanings (Tversky & Kahneman, 1985).

This organizational learning perspective on the knowledge transfer process thus suggests that knowledge transfer for innovation will benefit from an openness that encourages and allows multiple perspectives on problems (Boland, Tenkasi, & Te'eni, 1994). This might be manifested in KMS by having diverse knowledge available to reusers, allowing similar knowledge to be displayed in diverse ways, or encouraging searches for alternatives.

Organizational learning researchers have also focused on factors that trigger organizational learning. One such trigger is a reuser's perceived gap between actual and potential performance (Dosi & Marengo, 1993; Iansiti & Clark, 1994; von Hippel & Tyre, 1993); larger gaps force more organizational learning to occur. Another trigger is the institutionalized assumptions or norms that suggest that knowledge transfer and reuse is done for the benefit of the organization and this benefit will also accrue to the knowledge contributor and knowledge reuser. Thus, for knowledge transfer in innovation, an important driver will be the presence of factors that stimulate knowledge reuse, such as organizational incentives or performance gaps. In addition, research on new product development suggests that the nature of the project itself might be a trigger for knowledge reuse in the innovation domain. For example, Tatikonda and Rosenthal (2000) studied 120 "high-tech" new product development projects and found that technology novelty and project complexity created increased uncertainty, and that this uncertainty was reduced through knowledge reuse. This suggests that the novelty and complexity of the project may be triggers to reuse knowledge, when the reuse will help to reduce the uncertainty (Tatikonda & Rosenthal, 2000).

Resource Based View: Knowledge Capital as an Organizational Asset

The resource-based view is an economic theory of knowledge transfer in the firm. According to this view, the firm's resources and capabilities can be a source of "excess income" or "rent" generation (Barney, 1991; Dierickx & Cool, 1989; Lippman et al., 1982; Wernerfelt, 1984). To generate excess profits, the firm should have as many different organizational capabilities as possible: the more capabilities; the more likely that excess profits will accrue (Grant, 1996; Iansiti et al., 1994; Verona, 1999).

Capabilities that generate excess rent have been described as either functional or integrative (Verona, 1999), with both required. Functional capabilities allow a firm to increase its knowledge base while integrative capabilities act as an absorptive capacity by blending different technical competencies both from inside and external sources. A firm's integrative capabilities has been noted as a major contributor to excess rent generation (Cohen & Levinthal, 1990; Grant, 1996; Iansiti et al., 1994; Kogut et al., 1992; Teece, Pisano, & Shuen, 1997).

This perspective on knowledge management suggests, then, that a knowledge transfer process needs to ensure that individual knowledgebases are developed, rather than creating a single centralized knowledgebase. In addition, however, knowledge that integrates across the knowledgebases must be developed and stored in its own evolving knowledgebase in order to provide guidance about when and how to use the individualized knowledgebases. This integrative knowledge may be represented as automated meta-tags or search rules or as question and answer reminders to the knowledge reuser (e.g., "have you considered examining XYZ knowledgebase in your search for solutions?").

As Szulanski (2000) has pointed out, however, the resource-based view has ignored the fact that knowledge transfer can be slowed because it is laborious, time-consuming, and difficult; thus, costs to transfer knowledge must be considered. Moreover, the resource-based view ignores the process of knowledge transfer itself; that is, knowledge transfer occurs as a series of steps where opportunities for transfer must first be identified and distinguished from how transfer is executed. Szulanski's data indicated that certain factors affected knowledge transfer regardless of the step (e.g., reliability of the knowledge source positively affected knowledge transfer) while other factors were more important to specific steps in the knowledge transfer process (e.g., when the initial opportunity arises versus execution of the transfer itself). Szulanski's work thus suggests that, in addition to the resource-based view of developing individualized and integrative knowledgebases, knowledge transfer in innovative contexts may be differentially facilitated by motivation, organizational context, and task need, given the stage in the knowledge transfer process (Szulanski, 2000).

Table 1 summarizes the factors that, from our four streams of literature, may translate into minimal requirements for KMS facilitating knowledge transfer for innovation. The factors include a supportive knowledgebase (e.g., containing tacit and explicit knowledge), ways to interact with the knowledgebase (e.g., creation of shared artifacts), nature of the task (e.g., unanalyzability), organizational enablers (e.g., supportive culture), and individual variables (e.g., motivation). While these factors are shown here to be theoretically derived, their grounding in empirical research on innovation is limited. For example, Szulanski (2000) generated his factors based on a study of the transfer of best practices between firms, not the transfer of knowledge in such a way that innovative solutions were generated. Therefore, the intent of this paper was to examine a context of creative innovation to determine how these factors were manifested, and their precise role in influencing knowledge transfer for innovation.

---Insert Table 1 about here---

II. METHODOLOGY

We had the opportunity to explore knowledge reuse for innovation by examining six cases of innovative reuse across two space projects at the Jet Propulsion Laboratory. Both projects developed proposals for the design and implementation of scientific instruments to analyze the soil and atmosphere on Mars. For Project A, MECA, the proposal period lasted approximately 5 months. The proposal was selected via a competitive process, and the project which successfully developed the instrument ran from December 1997-September 2000. For Project B, MITCH, the proposal period lasted approximately 2 months. The proposal was partially selected via a competitive process, but due to external circumstances was not implemented. These projects were chosen because they each contained several examples of reuse for innovation and the participant-observer (one of the authors) had a significant role on, and therefore significant insight into, each of them. The cases were limited to examples of the reuse of technical or technology information, rather than management information (e.g., cost, schedule, planning) or administrative information (e.g., documentation)

Documents were reviewed for the two projects to identify cases of reuse for innovation. In total, 15 cases were identified. These 15 cases were arrayed along a continuum from adoptive reuse (e.g., the mere adoption of a knowledge contributor's knowledge into the knowledge reuser's project proposal) to adaptive reuse (e.g., the significant adaptation of one or more pieces of knowledge from a knowledge contributor to create an innovation described in the reuser's project proposal). Significant adaptations were determined based on the degree of change of form, fit, and function from the knowledge contributor's knowledge to that observed in the proposal. Time allowed us only to focus on six cases for intensive study. Therefore, we selected those six cases that provided the full range along this adapt-adopt continuum. Although we were primarily interested in the adaptive type of reuse (e.g., the type of reuse that leads to new knowledge), our six cases included two cases near the adoptive end of the continuum for comparison. The six cases are briefly described in Table 2.

---Insert Table 2 about here---

For each case, a set of key informants, representing both contributors and reusers, was identified. Table 3 indicates the job positions and roles of each key informant for each case

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Since the intent of our research was to identify factors that affected successful knowledge transfer for innovation, we developed an open-ended interview protocol, which we piloted on one of the team members. The protocol first defined knowledge reuse for the interviewee ("the use of an artifact to assist in the development of an innovative process or product") and the reuse case that was the focus of the interview. In this way, the interview focused the interviewee on a critical incident; a technique for interviewing that is superior to asking general questions. The questions led the interviewee to describe the problem that was being solved, what was being done to solve the problem prior to finding the knowledge, and how the knowledge was discovered. Additional queries concerned the characteristics of the knowledge that was reused (explicitness, nature of artifact), what factors helped the reuser to become assured of the applicability of the knowledge, and what the reuser did with the knowledge (e.g, degree of adaptation). Finally, the interviewee was asked about the importance of reuse to the project, personal motivation for reuse, and a timeline of events that transpired that eventually led to reuse. Interviews lasted from .5 hours to 3.25 hours (spread over several meetings), and resulted in a total of 103 pages of typed verbatim notes, taken by the interviewer.

To analyze the data, the notes for all six cases were organized by each protocol question. Then, the research team -- which consisted of a participant observer in the innovation cases, the interviewer, and an independent researcher -- assembled several tables to identify patterns across the cases. While the research team was familiar with the literature review discussed at the beginning of the paper, as an exploratory study, our intention was to identify factors that were derived from the interview notes, rather than impose factors from the literature. Therefore, we used a grounded theory approach (Glaser & Strauss, 1967) to identify the factors that appeared to present themselves across the cases. While such a methodology has only limited validity, it provides a useful means for identifying factors that previous research may have missed (Yin, 1994). In this sense, then, our methodology allowed us the opportunity to conduct a truly exploratory study.

III. RESULTS

Based on our analysis of the interview data, we learned about two aspects of knowledge reuse. First, we were able to identify eight factors that enable knowledge reuse for innovation. Second, we were able to describe a process by which reuse occurs

Factors Affecting Knowledge Transfer for Reuse

The eight factors are:

1) project experiences performance gaps
2) project requires risk-reduction
3) personal openness to examine broad set of knowledge to solve problem
4) broad personal knowledgebases that are readily searchable
5) team and organizational culture encouraging reuse
6) ability to quickly assess credibility and usability of reusable knowledge
7) ability to quickly assess degree of fit of reusable knowledge to problem
8) ability to quickly assess malleability and implementability of reusable knowledge

Each factor is explained briefly below. Appendix A presents interview notes for each case as it pertains to each factor.

1. Project experiences performance gap

Study participants in all six cases reported that whether or not they were inclined to consider reusing knowledge was in part stimulated by the existence of a performance gap, i.e., a set of requirements that could not be met by their existing knowledge or the knowledge of the team. For example, in the AFM Tip Array (TIPS) case, the knowledge reuser, a Scientist/Engineer, commented on the performance gap that encouraged him to look for existing knowledge that he might be able to reuse:

> "They had an operating system of tip arrays that they had developed and had a fabrication process to make them. This is a huge step forward. We immediately knew that we should team up (with the partner) as it would save time and money."

As another example, the Scientist in the Lidar case mentioned the performance gap of budget constraints that drove him to consider the Lidar prototype from the Champollion project:

> "The major problem was the cost cap. Full up development would have broken the bank."… "(The) key was not the availability of the instrument but the fact that the instrument was in development…"

Across the six cases, performance gaps were expressed in several different ways: as time constraints, as budget constraints, or as challenging performance objectives. However, the pattern across the cases was that the existence of one or more performance gaps created the motivation for reusers to consider searching for existing knowledge. Without the performance gap, the reusers may have relied on their own knowledgebase, including inventing their own solution. Thus, the existence of the performance gap stimulated the knowledge reuse process by convincing the reuser that existing solutions would not work.

2. Project requires risk reduction

Study participants from all six cases mentioned that they were motivated to look for artifacts they could reuse when there was a sense that risk reduction was an important criteria in the evaluation of their work. For example, the project manager for the AFM design commented:

> "I came out of the semiconductor industry where 100% reliability is demanded... I looked for companies that do this high quality work..."

Similarly, the scientist for the Electrometer Materials case commented:

> "We didn't want to be in the position for people to question why we chose a material...therefore we wanted to talk to the experts in space suits."

Since JPL's mission was one of creating solutions that have not been tried before, all solutions are essentially high risk. Thus, if there is a need to lower the risk, using another's solution may be preferable than inventing one's own solution-- and thus be a motivator for reuse -- if the contexts in which that solution has been tested previously are similar to the proposed context of future use.

3. Personal openness to examine a broad set of knowledge resources

Knowledge transfer in creative work often occurs in spontaneous, random ways (Allen, 1977). When knowledge transfer is limited to random person-to-person encounters, this creates a likelihood that individuals will only reuse knowledge from those with whom the reuser shares physical proximity, or from knowledge contributors who make themselves readily available to others (Davenport et al., 1998). Such limitations will then constrain the possibilities of reuse.

We found that our reusers countered this tendency to reuse knowledge from only a limited set of knowledge sources by adopting an openness to examining a broad set of knowledge sources to find the needed solution. The project manager (PM) of both Project A and B described his attitude about examining a broad set of knowledge as:

"We used to be farmers and we are now hunter-gatherers".

The PM explained this quote by saying, in the past, individuals preferred to invent their own solutions and work only with those immediately around them (e.g., "tilling their own soil, borrowing only from the neighbors"). New initiatives from the major customer, however, had encouraged the adoption of a new perspective of being open and willing to determine first if a solution existed somewhere before inventing one's own.

We found that our study participants in all six successful cases of reuse expressed this openness, not simply as an attitude but as embedded in the way they did their work. One way in which this openness was embedded in the way they did their work concerned how they defined the problem. Moreover, this openness was embedded in how the reusers did their work, such as defining the problem. Instead of defining the problem in terms of "how" the problem should be resolved (such as by assuming what scientific or engineering discipline would provide the solution, or pre-defining the set of suppliers most likely to have the solution), successful reusers defined the problem by the results they needed to achieve. This ensured that minimum success criteria for the project were clearly specified while allowing for the broadest set of solutions. For example, the reuser in the AFM Design case commented on how he defined the problem:

> “The problem was one of finding how to gather non-conducting samples of dirt. (We) needed a small package. (We) wanted high resolution at a few nanometers well below a micron. (We) needed an instrument that didn’t require high voltage or a vacuum.”

He did not specify what the instrument should look like, only the performance requirements he was trying to achieve. This allowed him the most flexibility for finding alternative solutions.

A second way in which this openness was embedded in how work was done was that the reusers explicitly did not limit their view of the solutions by traditional boundaries, such as only using solutions from government-sponsored suppliers, research and development organizations , or space-based scientific and engineering disciplines. In contrast, our study participants were willing to search for solutions in a variety of industries (semi-conductor, vacuum, chemical), sectors (academic, government, commercial) and scientific or technological fields (electrostatics, astrophysics, satellites). For example, the PM was willing to consider the electronic printed circuit board industry as a source for a solution to replacement of AFM tips.

A third way in which this openness was embedded in how reusers did their work was by not searching for point solutions when they looked in their knowledge repositories but instead searching by analogy. The knowledge reuser in the Electrometer Case was looking for reusable alternatives in testing electrostatic buildup on space suits and equipment:

> "I worked by analogy. (I) looked around to see what others were doing in the field:… semiconductor industry, electrostatic discharge industry. (There are) a

> number of companies that deal with clean room garments; chair covers (that require) a minimal static build up. (There was) some help from the textile industry, (for example, an individual) …from British textile industry."

A final way in which openness was embedded in how reusers did their creative work was that they recognized that innovation is serendipitous by nature and were willing to act on this recognition. Thus they functioned during the day by staying attune to opportunities for stimulating their thinking. This often meant seizing unpredictably upon the presence of an artifact or individual to begin a brainstorming process. For example, in the AFM Design case, the team was studying hazards for astronauts when Mars powdery dust is ingested or inhaled. The team felt the solution was likely to be grounded in a better understanding of how Mars dust adheres to different materials; so they needed to construct an instrument for testing a large variety of materials for their "stickiness", with only a small amount of actual Mars dust available to them. The PM explained how the solution - the "sample wheel" design - came about:

> "We were in the cafeteria. This prototype is the same size and shape as throw-away Styrofoam dessert plates (with a flat bottom and 45-degree sloping sides). Innovation here is if you take an object with a 45-degree slope, (and put a hole on that slope) when the hole is at the top, it will be horizontal for pouring the dirt in. When it rotates and gets to the bottom, the hole becomes vertical and the excess sloughs off and becomes very close to perfect for looking at the substrates under the microscope. In each of the holes, we put a different substrate. Simple rotation, nothing like this had ever been designed before. We were looking for simplicity. We wanted to build this with only 2 degrees of freedom."

Thus, the openness to serendipity allowed the team to use a Styrofoam dessert plate encountered during their lunch hour to provide the basis for an innovative design.

4. Broad personal knowledgebases, readily searchable to find reusable alternatives

An openness to examining a broad set of knowledge sources is of little value if the broad knowledge sources are not readily available and searchable. Study participants in all six cases reported having extensive personal knowledgebases of people, research centers, research papers, suppliers, and physical prototypes. These knowledgebases were personally developed over time based on extensive networking, professional activities, and previous project experience. The knowledgebases were not often electronically organized but did often include extensive personal address books, extensive lists of electronic bookmarks, and/or having a well-articulated network structure indicating who they should call about different kinds of problems. When a new problem arose (as when it was posed by a new client or AO), the reuser would draw on that personal knowledgebase to determine whom to ask about different aspects of the problem.

An examination of the knowledgebases used by the study participants indicated that they adhered to Granovetter's (1973) weak-tie theory. Granovetter postulated that distant and infrequent relationships (weak ties) are more efficient for knowledge sharing due to bridging previously unconnected groups, developing broader access to more organizations, and less prone to redundant knowledge (Granovetter, 1973; Hansen, 1999). These weak ties could be seen, for example, in the Electrometer Materials case:

The problem was one of selecting materials for electrostatic testing that would be found in a space mission, such as space suit fabric, boot materials, glass, plastics and other equipment materials. One of the scientists on the project team met a knowledge broker from another NASA center at a professional meeting. This intermediary was asked about possible solutions to their problem. While the person did not have the required solution, he did have suggestions of people they might contact. After making that contact, further recommended contacts were offered. Finally, after following the path of recommendations, the right partner with the right solution was identified as a group of scientists who had studied and measured a specific set of materials that could be re-tested by the MECA team. The engineer on the Electrometer Materials case recalls,

> “(Some scientists at) Kennedy (Space Center) helped find the materials. Initially I had no idea they had worked in this field. There was someone around, (a scientist, who) was working with MECA on patch plates and he may have had the Kennedy connection.”

This case indicates that, for our study participants, the knowledgebase of weak ties was as valuable as the internet and electronic search tools.

5. Culture of the organization

Study participants repeatedly referred to JPL's organizational culture as affecting knowledge reuse, referencing in particular the NIH "not-invented-here" culture:

> "The NIH syndrome is extreme at JPL. They believe they are world class in everything, and will spend a lot of time reinventing (something) that they could get from collaborating with an outside group."

> "Where isn't there not invented here? We have as much hubris as anyone (does) and NIH is rampant. Are we still going to let (a supplier) do these things or do it ourselves?"

However, several participants mentioned that the culture was changing, which contributed to increased reuse. For example, the PM commented:

> "(NIH) has been tempered, in recent years, by entreaties (by the customer) to partner and ally with other firms and academics. Forced downsizing of JPL gives no option as to whether to partner. You find that you may have better luck outside than inside with certain technologies.”

As a result, several commented that the current culture was one of sharing:

> “There are cultural norms inside NASA to share.”

> “At JPL there is a sharing culture, we work hard at it (entertaining, house parties, dinners etc.). People are exceptionally ethical. People have trust that their knowledge won’t be misused and then cut loose. People are relaxed.”

Thus, our participants had perceived a cultural shift at JPL where reuse was now not only culturally acceptable, but also encouraged.

6. Ability to quickly assess the credibility, utility and feasibility of potentially reusable knowledge

In all six cases the ability to quickly assess the credibility of the source was critical to encouraging reuse. For example, a reuser in the AFM Design case noted that when contacting the potential partner:

> "We knew his reputation, and thus, trusted his designs".

In the Lidar case, the project manager commented:

> "I had confidence in him".

Even in the Electrometer Materials case, in which the project team worked with partners with whom they had no previous working relationship, the ability to quickly develop confidence in the source was critical to the success of the transfer. In the words of the knowledge reuser,

> "We worked with the people at Kennedy Space Center to design the electrometer experiments on various materials. While working with the data was important, it was equally if not more important to have a lot of discussions and meetings. This was more about building relationships (than about testing materials)."

Another reuser in that same case mentioned why they went with the partner. According to the reuser, the partner was well known in the field of materials testing:

> “Number one reason was that these (people) were recommended and it developed our credibility by using their credibility.”

While the interviewees agreed that an ability to quickly assess the credibility of the knowledge contributors was critical to the reuse process, reusers described different ways in which that credibility was assessed. Some reusers assessed credibility through reputation reported by others; other reusers assessed credibility through conversations to assess the confidence and validity of the data on which judgments were based; and still other reusers assessed credibility by examining concrete artifacts. Frequent comparison between the model or "template" or artifact and the replica being created, entailing exchanges of information between the source of the knowledge and the receiver assisted in the process of transfer. The reuser in the Electrometer case, purchased a commercial off-the-shelf electrometer in order to assess its testing properties:

> "Then, upon meeting with the electrostatic specialists at (the partner firm), I observed a large measurement apparatus. I had the idea of combining the electrometer with the insulators as integral to the instrument. When I saw Gompf's machine it was a physical proof of concept."

We found that reusers benefit from the ability to quickly assess credibility of the source, however, they exercise wide latitude in how those assessments are made.

7. Ability to quickly assess the degree of fit of potentially reusable knowledge.

The Project manager pointed out the difficulty of simply adopting existing solutions:

> "You cannot use just any machine on Mars. For example, you cannot use your laptop computer on Mars. There may be problems of radiation hardness of chips, resistance to shock and vibration, resistance to dust. You usually have to invent the hardware from scratch."

Thus, to reuse existing knowledge requires a very clear concept of the performance targets and then determining the extent to which the potentially reusable knowledge currently fits (or can be modified to fit) those targets. The reuser in the AFM case was able to identify several possible existing microscopy solutions. However, upon further examination, only the AFM met the tight performance requirements that would allow viewing of non-conducting particles, below one micron in size. He discusses the team's assessment of fit:

> "We know that the basic requirements (to operate an) AFM are quite modest. You can run it in air (vs. vacuum) and you don't have to do much (sample) preparation. You can get the head compact and in a good package to fly. We had experience with getting SEM (the other option) qualified for space and it had not been qualified up to now. Thus we saw the benefits of using the AFM over the SEM. (We) thought briefly of the scanning tunneling (microscope, the third option), but you must have a conducting sample and this type of sample is not expected on Mars."

The study participants reported that an ability to quickly make these fit assessments was often critical to whether existing knowledge solutions would be reused since each participant had very large and broad knowledgebases to search. They needed to apply quick scanning techniques to their searches in order to determine useful alternatives within the schedule.

In the case of the AFM Tip Array for example, the reuser assessed fit by calling a well-known professor to find out what he was doing in the field of scanning tips for semi-conductors.

> "I talked to (the professor)'s post-graduate student via telephone and he mentioned that they were working on tip arrays. I checked their website for downloaded specifications and pictures of the array. We then invited the professor into a teleconference of the MECA proposal team. I then went up there to meet him while I was seeing other people in the Bay area."

This all occurred in a few weeks time, and helped with the assessment of the usefulness of the knowledge. Thus, in all six cases, the ability to quickly assess fit between a possible reusable solution and the problem determined whether or not knowledge transfer was successful.

8. Ability to quickly determine the malleability of the reusable alternatives.

In four of the six cases, participants reported adapting the reused solution. In the other two cases, although the solution was primarily adopted, minor adaptation was required. This meant that in all cases, the reuser needed to assess the degree to which any requirements not currently met by an available solution *could* be met, given modifications to the design. Reusers relied on several inputs to make this assessment. One such input was the degree of involvement of the knowledge contributor. If the contributor was willing to only be tangentially involved in the reuse, then knowledge transfer was less likely to succeed. For example, in the Magnetic Patches case, the engineer described the role of the knowledge contributor:

> "(The knowledge contributor) critiqued the design based on his experience on the Mars Polar Lander and Mars Pathfinder. He participated in every aspect of the experiment."

In addition to the input of the knowledge contributor, reusers assessed the likely malleability of the available solution by examining the trajectory of past design modifications for that solution. If previous modifications had been made to an available solution, and those modifications were in the direction required for the performance targets, then reusers often inferred that the design was sufficiently malleable to warrant serious attention. For example, the electrometer assembly in the Electrometer Design case needed to be extremely compact to fit within the scoop of the robot arm. The engineer had produced several iterations of a design that began to yield smaller and smaller packages. Although the performance criteria had not yet been met, the trajectory of improvement in the design was in the right direction. It was likely that the miniaturization would be adequate by the time the instrument was assembled. The engineer turned out to be correct in his assessment:

> "By the time the last prototype was built, all six instruments (electrometers) fit into the heel of the scoop."

A final input in determining malleability is the question of plausibility of implementation. Participants reported that several questions formed the basis for this determination: 1) is implementation possible, 2) is assistance available (from the source, from the inventor, from the manufacturer), 3) are the required models, prototypes, specifications and data available and 4) are the models sufficiently transparent for rapid modification? For example, in the Lidar case:

> "the prototype was available and could be modified for the intended use with the assistance of a Canadian partner who had designed it for the Champollion project."

In the Electrometer Materials and Magnetic Patches cases, the partners were willing to provide the materials that had been pre-tested for space as well as the test data. The machine that measured the electrostatic properties was a "proof of concept", according to the reuser, where the design was adaptable, after miniaturization, to the project objectives

Generalizing the Factors

Examining the eight factors that were found to affect knowledge reuse for innovation indicates that the factors can be grouped into more abstract (and thus generalizable) sets of factors. These sets include those factors associated with:

1) Task Objectives (e.g., performance gaps and risk reduction requirements),

2) Individual Abilities (personal openness, broad personal knowledgebases),

3) Organization's Integrative Capacity (e.g., culture encouraging reuse),

4) How the Potentially Reusable Knowledge is captured, displayed, and interacted with (e.g., ability to assess credibility, degree of fit, malleability, and implementability of knowledge), and

The correspondence of this more general set of factors to the literature, cited at the beginning of this paper, is readily apparent. The organizational learning literature described triggers of the reuse process as being grounded in a performance-based need. We found that participants were more likely to reuse knowledge when there was a performance gap and risk reduction requirements that could not be solved through pure invention. The resource-based view of the firm espouses the need for firms to foster both individual functional ability as well as the ability to integrate across individual functions. We found that participants were more likely to reuse knowledge when they had the personal ability to do so (by having an openness, a broad personal knowledgebase to search), and the organizational culture encouraging reuse. Finally, just as the knowledge creation and common ground models suggest that both tacit and explicit knowledge must be transferred, we found that we were able to identify the components of this knowledge that needed to be transferred - components that represented both tacit and explicit knowledge. These components included information for a potential knowledge reuser to assess the credibility, usability, and degree of fit, malleability, and implementability of the knowledge being considered for reuse. Our more general model of these abstracted factors is presented in Figure 1.

---Insert Figure 1 about here---

While our four abstracted factors have grounding in the existing literature, they go beyond the existing literature by being more specific. Openness is not simply an attitude variable but is described in the terms of how reusers work. Characteristics of the knowledge in a knowledgebase are described in terms of the assessments that must be made on that knowledge, not simply as tacit vs. explicit knowledge. And the characteristics of broad personal knowledgebases that are readily searchable are described for the innovation context. In addition, the distinction was made in the case selection between adaptive versus adoptive reuse; however, the data are sparse in showing whether the factors affect each adapt vs. adoptive reuse differentially. This suggests then that the jury is still out on whether the distinction between adoptive and adaptive reuse is an important one.

Process-Based Model

The model in Figure 1 describes a variance-based model, indicating four generalizable factors likely to impact reuse for innovation. In addition to this variance model, our detailed case analysis allowed us to suggest a model of how the knowledge-transfer process unfolded over time. The model is displayed in Figure 2.

---Insert Figure 2 about here---

In this model, knowledge reuse is shown to be triggered by the need to identify alternative design solutions to meet a set of project requirements. If an immediate search of the designer's broad personal knowledgebase indicates an existing solution that is credible, usable, fits with project requirements, and implementable, then that solution will be readily adopted. However, if the search indicates that existing solutions still leave an unresolved performance gaps and risks, then the designer must engage in a more proactive search for solutions. If the organization's culture encourages reuse, and the individual has a broad knowledgebase available to him, then adaptation becomes a feasible option. Adaptation will only occur, however, if the designer can readily assess the credibility, usability, degree of fit, malleability, and implementability of various design alternatives. These assessments are typically made by directly interacting with the knowledge contributor. However, the assessments could be made through interaction with the knowledgebase itself, if the knowledge and interface are appropriately structured.

Throughout our interviews, we found evidence of the efficacy of this model. The first step in the process is to examine project requirements and determine the need for reuse. According to the Project Manager, in examining the project requirements,

> "We wanted to know about the soil and dust on Mars, the toxic components, electrostatic properties, size and shape of particles. (The) important thing is how do particles find their way into your environment. No one is outside taking a breath of air. How does dust interact with the human environment? It tracks in on suits, machines. What will be attracted to fabric, materials, etc? How do you prepare a field of view that does not have too much dust? How do you study the particles and how they stick and to what?"

Thus, the project requirements encouraged the PM to begin to examine alternatives.

In the next phase, alternatives are identified. The process is triggered by the perception of a performance gap between existing solutions and an optimal solution and risk reduction requirements. We noted that the identification of alternatives in the Project A used the broad personal knowledgebases and openness of the participants. This finding was confirmed by several comments, including the following by the PM in regard to the AFM Design,

> "These microscopes are tools. The problem (is that) of looking at particles. Each of us had different instrument specialties. What drew me in was my expertise with the Scan Probe Microscope (SPM), which includes a specific type of SPM, the Atomic Force Microscope (AFM). Another type of SPM is the Scanning Tunneling Microscope (STM), there are also thermal (microscopes) and others."

Having identified the alternatives, the reuser must be able to quickly assess each alternative for credibility, fit, malleability and implementability. If a reusable solution is found, based on the reuser's evaluation, the alternative under consideration for reuse may either be adopted "as-is", adapted, or not reused. In the Project A, the team was able to adopt most of the technology from Pathfinder and Mars Polar Lander for the Magnetic Patches and for the materials used in the Electrometer and Patches experiments. However, extreme adaptation was necessary for both the Lidar and the Electrometer Design. In addition, the special needs of high quality and longevity of the final product are also major considerations as discussed by the reuser in the Magnetic Patches case,

> "When you design something that can't be serviced later, it is very different than anything that is done anywhere else on the planet. To be able to do engineering that has no mistakes is not really taught in engineering schools (except for the design of pacemakers and atom bombs). JPL specializes in making things work for long periods of time in hazardous environments."

It should be understood that the reuse process is not an island. During the development and implementation phases, this process may be revisited again if it is determined that the chosen alternative will not be suitable due to cost, time, performance, availability of suitable expertise or partners for the solution chosen.

There are several elements of this process model that we believe go beyond existing models, such as those suggested by Nonaka (1995), Szulanski (2000), and Von Krough (2000). First, our model suggests that reusers may choose not to reuse, to adopt, or to adapt at any point in the knowledge transfer process. Their choices are based on information that they are continuously gathering and the assessments they are making about the knowledge itself, and how the knowledge fits their problem. Thus, rather than viewing the knowledge transfer as a sequential flow process, it is much more like an emergent knowledge process (Markus, 2000), one in which bits of knowledge are being related with other bits of knowledge and synthesized to a final decision. Second, the model suggests that reusers adapt the knowledge, even as they are deciding whether or not they might want to adopt, adapt or discard the knowledge. That is, by assessing the credibility, usability, degree of fit, malleability, and implementability of the knowledge, the reusers are likely to be eliciting additional information about the knowledge, which in turn alters the knowledge. Thus, as pointed out by Weick (1995), Brown & Duguid (1998), Hutchins (1991) and others, knowledge is not an objective reality but rather a subjective interpretation of data that will change as new data is brought to bear. Finally, the model suggests three key leverage points for when and how to encourage reuse:

1) When alternatives are being identified (at which point broadening out personal knowledgebases is valuable),
2) When alternatives are being assessed (at which point, providing the information necessary to make assessments is valuable), and
3) When reuse is selected and needs to be implemented (at which point, the expertise, interest and cooperation of the parties is valuable).

IV. CONCLUSIONS

This research has three implications. First, a number of hypotheses about knowledge reuse in innovation are suggested that warrant testing.

Hypothesis 1. Performance gaps experienced in a project, including time criticality of the project, cost limitations of the project, and unmet performance will be positively related to knowledge reuse.

Hypothesis 2. Where reuse can fulfill risk reduction requirements, it will be positively related to knowledge reuse.

Hypothesis 3. Team members' personal openness to knowledge reuse as manifested in the way they do their work will be positively related to knowledge reuse.

Hypothesis 4. Team members' broad personal knowledgebases and active knowledge searching to find reusable alternatives will be positively related to knowledge reuse.

Hypothesis 5. The culture of the project team and parent organization that encourages knowledge sharing and reuse will be positively related to knowledge reuse.

Hypothesis 6. Team members' ability to quickly assess the credibility of a source, the utility and feasibility of the knowledge and reusable alternatives will be positively related to knowledge reuse.

Hypothesis 7. Team members' ability to quickly assess the degree of fit of the reusable alternatives will be positively related to knowledge reuse.

Hypothesis 8. Team member's ability to quickly determine the degree of malleability of the reusable alternatives will be positively related to knowledge reuse.

To test these hypotheses, we suggest that further research on larger sample sizes of cases of reuse be conducted.

A second implication of this study is for theories of knowledge management. Our research suggests that knowledge reuse research should spend less time debating whether tacit versus explicit knowledge is required for knowledge transfer and more time on articulating what might be the attributes of the knowledge that need to be articulated for knowledge transfer to occur. Moreover, the distinction initially made between adaptive vs. adoptive cases of reuse warrants further study. Finally, the generalizability of these findings warrants investigation. The cases involved highly skilled knowledge contributors and reusers, highly motivated to succeed at a new innovation. Thus, these participants were particularly adept at learning from artifacts quickly as well as substantial experience in the field. The extent to which these factors generalize to cover innovations, which require less substantial expertise, remains to be seen.

A final implication of our research is on the design of KMS. We have found that, knowledge transfer for innovation required learning, not just information transfer. All six cases primarily relied on human-to-human contact for this learning to occur - to find the right individuals with the right solutions, to query the individuals to assess the applicability and limitation of the solution, and to physically manipulate the solutions to personally assess their appropriateness. Such human-to-human techniques are limited to an existing set of contacts. It's hard to cold-call someone new to find a solution. If KMS can facilitate human-to-human contact by providing knowledgebases of initial information about the applicability, malleability, and quality of various solutions, then the follow-on human-to-human contact is made more efficient and focused. In addition, if such KMS can provide the proactive search techniques to allow unexpected connections to be made through rapid prototyping, simulations, querying, and modeling, then follow-on human-to-human contact is further enhanced. Finally, we have suggested some initial organizational requirements for such KMS: the organization must have the organizational culture to encourage reuse, hire and/or train employees to incorporate openness for reuse into how they do their work, and create a sense of urgency in which performance gaps and risks will be unsatisfactorily resolved without reuse.

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TABLE 1

Summary of Literature on Factors Facilitating Knowledge Transfer

Stream of Research	Example References	Factors that may facilitate knowledge transfer in innovation
Knowledge Creation and Knowledge Management	Bresman, Birkinshaw, & Nobel, 1999; Kogut & Zander, 1992; Nonaka, 1991; Nonaka & Takeuchi, 1995; Sherman & Lacey, 1999; Von Krogh, Ichijo & Nonaka, 2000;	- Allow knowledge contributors to blur distinctions between tacit and explicit knowledge - *Encourage knowledge contributors to share tacit and explicit knowledge about local use and ideas for global use* - Allow knowledge reusers to experiment with combining internal and external knowledge in various ways
Common Ground	Brown & Duguid, 1991, 1998; Clark, 1996; Clark & Brennan, 1993; Cole, 1999; Davenport & Prusak, 1998; Katzenbach & Smith, 1999; Lipman-Blumen, 1999; Majchrzak, Rice, Malhotra, King, & Ba, 2000; Ouchi, 1980; Tsoukas, 1996	- Allow knowledge contributors to share for each contribution assumptions about objectives, constraints, analytic methods, and knowledge acquisition, evaluation, and use norms - Help knowledge reusers to translate these assumptions through creation of shared artifacts with contributors
Organizational Learning	Dosi & Marengo, 1993; Huber, 1991; Iansiti & Clark, 1994; Ireland, Hitt, Bettis, & DePorras, 1987; Senge, 1990; Tatikonda & Rosenthal, 2000; Tversky & Kahneman, 1985; von Hippel & Tyre, 1993; Walker, 1985	- Allow multiple perspectives for viewing problems - Organizational incentives, performance gaps, and project uncertainty stimulate reuse
Resource-based View	Barney, 1991; Cohen & Levinthal, 1990; Dierickx & Cool, 1989; Grant, 1996; Iansiti et al., 1994; Kogut et al., 1992; Lippman & Rumelt, 1982; Teece, Pisano, & Shuen, 1997; Verona, 1999; Wernerfelt, 1984	- Allow for creation of multiple individualized knoweldgebases - Encourage development of a knowledgebase that provides guidance on how to integrate across individualized knoweldgebases - Individual motivation, organizational context, and task inanalyzability affect reuse

TABLE 2
Brief Description of Six Key Cases

Case	Description	Adopt vs. Adapt Continuum
Magnetic Patches (MAG)	Adoption of previous Mars magnetic experiment on materials, to fit into new Mars mission in different size package.	Almost Strictly Adopt
Electrometer Materials (EL-M)	Adoption of existing set of materials from Kennedy Space Center collection for use in electrometer. Actual materials as well as test data were available	Mostly Adopt
AFM Design (AFM-D)	Adoption of an atomic force microscope (AFM) used in the semi-conductor industry to test surface smoothness, to be used on Mars to characterize particles.	Mid Range between Adopt and Adapt
AFM Tip Array (TIPS)	Adaptation of technology concept to use multiple AFM tips to increase scan speed in semi-conductor industry, to instead provide redundancy for operation on Mars through reusable tips for AFM.	Mid Range between Adopt and Adapt
Electrometer Design (EL-D)	Adaptation of industrial electrometer for use on Mars by combining rubbing and measuring functions in one instrument to test the electrostatic properties of materials for equipment and space suits	Mostly Adapt
Lidar (LID)	Adaptation of Laser Radar (Lidar) from previous mission where it was used for hazard avoidance to use on surface of Mars to detect dust devils.	Almost Completely Adapt

NOTE: Cases are arrayed from top to bottom, from the closest to strict Adoption to the most Adaptation

TABLE 3
Key Informants for Six Key cases

Case	Informants	Informant's Role
Magnetic Patches (MAG)	SCI ENG ENG	KC KR PA
Electrometer Materials (EL-M)	PM SCI ENG	KR KC KR
AFM Design (AFM-D)	PM SCI/ENG	KC, KR KC, KR
AFM Tip Array (TIPS)	PM SCI/ENG	KR KR
Electrometer Design (EL-D)	PM SCI ENG	KR KC KR
Lidar (LID)	PM SCI ENG	KR KC, KR PA

Informants

PM = Project Manager
SCI = Scientist
ENG = Engineer
Note: Some informants played dual roles

Informant Roles

KC = Knowledge Contributor
KR = Knowledge Reuser
PA = General Participant (Managing, Coordinating)

APPENDIX A

Factors 1- 3 for Magnetic Patches and Electrometer Materials Cases: Quotes and comments

#	Factor	Magnetic Patches	Electrometer Materials
1	Project that is experiencing performance gaps	4 Parts: 1) ENG: (mounting) "(The) threaded insert with spring washer applies tension to the spring for hard materials (and the) gaps provide for differential expansion. Fabrics are stretched and held in place by springs. (The) advantage of the system (is that there are) no chemicals, lubricants or glues affecting the dust adhesion." 2) ENG: (mechanism) "Method of holding samples in a secure way during launch and transit then deploying them on the surface of the arm." 3) ENG: (selection) "Choosing a suite of surface materials that had a wide range of surface properties." 4) ENG:(data interpretation) "This is a calibration issue. From the photos with the RAC (robot arm camera) we can determine that the dust is adhering and with what accuracy (this is reflected) in the other experiments."	SCI: "MECA had requirement to measure the dust interaction in the AO. Group at Kennedy looking at electrostatic discharge of materials where ground crews have materials that cause sparks on the launch pad. Shoes, garments etc. are approved…It is not easy to predict it is not only the material, it is how it is processed and woven (that causes its triboelectric properties)."
2	Risk-reduction requirements	ENG: "(The) latch design solves for limited error of Robot Arm. This is just standard robotics. Latch was double over the center device, standard. (The) arm moves and engages the latch…To close it, it operates in reverse and pushes the plate closed. …NASA uses these all the time. (The spring is) reasonably protected from dust on Mars, including contamination kicked up on landing." ENG: "JPL made the decision to have industry do our engineering. That implies that anyone can do what we do. I don't think that is the case. This has caused failures. The Mars Polar Lander was entirely subcontracted. Grand management decision to not reuse the knowledge." SCI: "MECA patch plates was without a doubt useful. It was helpful, all the lessons learned...The heritage and scrutiny of a mature and complete previous experiment on Mars would validate all the MECA."	SCI: "We didn't want to be in the position for people to question why we chose a material…therefore we wanted to talk to the experts in space suits."
3	Personal openness to examine broad set of knowledge to solve problem	ENG: "There are other places I could have found that expertise, maybe from another flight project, but he (ENG on Pathfinder) was critical for thinking through the design…It would have taken very much longer. I cannot stress enough the critical nature of this. It took them (ENGs on Pathfinder and Mars Polar Lander) some years to work this out. The work started in the early 90s. The (ENG on Mars In Situ Propellant) experiment might have been able to help me with this (magnetic patches experiment design)." SCI: "Getting the Danish (SCI partner) help and input for the Getting the Danish (SCI partner's) help and input for the MECA patch plates was without a doubt useful. It was helpful, all the lessons learned. The heritage and scrutiny of a mature and complete previous experiment on Mars would validate all the MECA information."	ENG: "I worked by analogy. (I) looked around to see what others were doing in the field … semiconductor industry, electrostatic discharge industry. (There are) a number of companies that deal with clean room garments, chair covers (that require) a minimal static build up. (There was) some help from the textile industry, (for example, an individual) …from British textile industry." ENG: "KSC had been engaged in selection of electrostatic materials for 20 years. So I was able to tap into that database."

APPENDIX A

Factors 4-6 for Magnetic Patches and Electrometer Materials Cases: Quotes and comments

#	Factor	Magnetic Patches	Electrometer Materials
4	Broad personal knowledgebases that are readily searchable	ENG: (re data interpretation) “I think what happened is I was talking with (ENG on Mars Pathfinder camera) and he said, ‘how will you interpret the data?’ He said you better solve that problem. The experimental concept takes a little more sophistication. Robot mechanisms are all over the world, but in situ dust adhesion experiments, there aren't that many people trying to do that.” ENG: “(The SCI on MECA) contacted (SCI partner) before I became COG-E. He asked (SCI partner) to provide patch plate material. He found (SCI partner) through the article the (SCI partner) had written.” ENG: “I rely on people I know. This is more designed than serendipitous.”	SCI: “Kenndy knew we were doing this work through a website or abstract that we were going to look at the interaction of Martian soils on materials in space. I met (an individual) from KSC at a meeting of the Mars Society in Boulder, CO. (He) introduced himself and followed up with an email.” ENG: “(Some scientists at) Kennedy helped find the materials. Initially I had no idea they had worked in this field.” “There was someone around, (a scientist, who) was working with MECA on patch plates and he may have had the Kennedy connection.”
5	Team and organizational culture encouraging reuse	ENG: “Encouraged (in reuse), by (PM) in particular. He was exceedingly supportive of my work…Encouraged (in reuse), by (PM) in particular. He was exceedingly supportive of my work.” ENG: “Within JPL there is a trend among young engineers to think there is nothing to be gained by speaking to the older engineers. JPL could do much more to foster the continuity of knowledge than JPL does. There are a lot of people you can (still) find, but once the senior engineers retire, they will take their knowledge with them. There is no good solid mechanism for preserving that knowledge and reusing it. This problem has been brought out by recent failures in Lockheed Martin experiments.” ENG: “ My peers encourage (knowledge sharing and reuse). I have never approached anyone without having a warm, 'I'll talk with your for 20 minutes about that'. Culture that says you have a responsibility to show up for a peer review or read an article that someone wrote.”	SCI: “The NIH syndrome is extreme at JPL. They believe they are world class in everything, and will spend a lot of time reinventing a knowledge base that they could get from collaborating with an outside group. JPL is world class in many things, but not everything. There are not unlimited resources to develop an in-house knowledge base about everything.” ENG: “Trust was in place from the beginning because we saw a need for one another. Both parties had critical pieces of the technology. JPL had the instrumentation and KSC (had) the materials…Cooperation between JPL and KSC exists today and it was borne out of this activity.” ENG: “In the case of the JPL/KSC interaction, we developed a cooperative relationship. The root of this cooperation is the arrangement that JPL builds the instruments and KSC performs the tests. KSC then provides test results which helps in developing the next improvement.”
6	Personal interest in the technology or science and opportunity to learn in regard to encouragement to reuse.	ENG: (Adopt) “Used knowledge from (scientists from University of Arizona and the) Pathfinder camera. He observed dust adhesion and we used his exact materials for measurements and (the same) science as was used on Pathfinder to compare the two projects.” SCI: 15 years, excited about opportunity to learn, needed to develop trust to assess risk, to reuse, to believe the other party would not take advantage of the relationship to build the relationship “The way we reused knowledge was by getting their help. This was efficient. If we had copied (instead of adopting) would we have done it right?”	ENG: Little experience with materials, but excited about the project as an opportunity to learn. “KSC had been engaged in selection of electrostatic materials for 20 years. So I was able to tap into that database.” SCI: Had been in the field one year and seemed only mildly interested by his comment, “the experiment seemed OK and interesting” . His answer showed an interest in relying on the experts: “Triboelectricity is new to me and we were consulting experts.”

APPENDIX A

Factors 7 – 9 for Magnetic Patches and Electrometer Materials Cases: Quotes and comments

#	Factor	Magnetic Patches	Electrometer Materials
7	Ability to assess credibility and usability of reusable knowledge	ENG: "(The) surface of the patch plate was the same as that used on Pathfinder, magnesium material, bead blasted with a specific process and then platinum plated and carefully handled…(We) used (the knowledge giver's) handling instructions and bead blasting instructions." ENG: "Secure and confident. If we were using one of the 'gems' of the Pathfinder (mission), that we were sort of riding on their experimental record. The team shared that. It improved our credibility." ENG: " I had a firm trust in (SCI partner), in particular the caliber of his published experimental work. I got this before I met him. His Pathfinder data was the most scientifically valid. I viewed him as a very rational and dedicated scientist...His knowledge had a great weight with me. I had a desire not only to obtain the knowledge, but also to go directly to the source."	ENG: "We worked with the people at Kennedy Space Center to design the electrometer experiments on various materials. While working with the data was important, it was equally if not more important to have a lot of discussions and meetings. This was more about building relationships (than about testing materials). SCI: Number one reason was that these were recommended and it developed our credibility by using their credibility. …This was not MECA expertise." "(There were) several reasons for reuse: 1) another NASA center, 2) fact that they had been looking at this for almost 20 years, 3) they had looked at ...data sheets for 100s of materials, 4) provided access to 70 or 80 materials that had current data, 6) they were a NASA knowledge center for material data."
8	Ability to assess degree of fit of reusable knowledge to problem	ENG (special need of quality & longevity):"When you design something that can't be serviced later, it is very different than anything that is done anywhere else on the planet. To be able to do engineering that has no mistakes is not really taught in engineering schools (except for the design of pacemakers and atom bombs). JPL specializes in making things work for long periods of time in hazardous environments." ENG: "There were other solutions that were valid that I had to reject. For example (the ENG on Pathfinder) had an additional mechanism for maintaining a pristine condition of the patches, but I didn't have time to wait for this functionality...ran out of time and weight (constraint)."	SCI: "They went further to say they would not jusst recommend, but would provide materials and pre-test them (they volunteered to be a procurement conduit…This was of tremendous value to MECA. (There was) synergy, their extensive knowledge of electrostatics provided materials that had undergone other studies."
9	Ability to assess malleability and implementability of reusable knowledge	ENG: "(The knowledge giver) critiqued the design based on his experience on the Mars Polar Lander and Mars Pathfinder. He participated in every aspect of the experiment." SCI: "These experiments were attractive not just because they had some heritage on Mars, but also because of their relative simplicity." SCI: "We had a different experimental configuration and an enhanced experiment capability, different magnet size, ability to look close up (camera), able to remove dust, deliver soil samples to the magnets from the surface and sub-surface."	SCI: "The only known is the behavior of the materials. Tendency to charge up, weathering tendencies in exposure, ability to hold up under prolonged use. We could adopt that knowledge. The fact that the group was trusted (it was NASA) would assist us in being sure that these materials would be relevant. Time was (also) a factor in that these had been re-tested."

APPENDIX A

Factors 1- 3 for AFM Design and AFM Tip Array Cases: Quotes and comments

#	Factor	AFM Design	AFM Tip Array
1	Project that is experiencing performance gaps	PM: "You have a sparse particle field and you want to look at a lot of particles. You want single particles and lost of them. Translate what you would do on earth to make the slide…How do you prepare a field of view that does not have too much dust? ...(Solved the problem see below factor 3) Innovative idea is lying the microscope on its side. Also solves the problem of the verical instability of the microscope."	SCI/ENG: "We knew we needed to use more than one scanning tip. (These) need to be exchanged for fresh tips during the mission. Each tip is good for a few hours of scanning time...the mission is 21 days, and we have 8 tips." SCI/ENG: "They had an operating system of tip arrays that they had developed and had a fabrication process to make them. This is a huge step forward. We immediately knew that we should team up (with the Stanford team) as it would save time and money."
2	Risk-reduction requirements	PM: "I came out of the semiconductor industry where 100% reliability is demanded. Instruments must work in a vacuum, at high and low temperatures…(I) looked for the companies that do this high quality work in the area of surface interface. These firms had been in the vacuum industry for decades. Looked for inspiration to this industry. In particular we said we wanted as few degrees of freedom as possible."	SCI/ENG: "Once the concept of the array was selected for implementation, it was the (fabrication team's) responsibility to to fabricate the arrays. As they had the necessary expertise to complete this at low risk, I was quite happy for (them) to handle this." SCI/ENG: "They had an operating system of tip arrays that they had developed and had a fabrication process to make them. This is a huge step forward. We immediately knew that we should team up as it would save time and money. In fact we would save hundreds of thousands of dollars and many months to a year or more of time."
3	Personal openness to examine broad set of knowledge to solve problem	SCI/ENG: "The problem was one of finding how to gather non-conducting samples of dirt. (We) ...needed a small package. (We) ...wanted high resolution at a few nanometers well below a micron. (We) ...needed an instrument that didn't require high voltage or a vacuum." PM: "We were in the cafeteria. This prototype is the same size and shape as throw away Styrofoam dessert plates (with a flat bottom and 45-degree sloping sides). Innovation here is if you take an object with a 45 degree slope, when the hole is at the top, it will be horizontal for pouring the dirt in. When it rotates and gets to the bottom, the hole becomes vertical and the excess sloughs off and becomes very close to perfect for looking at the substrates under the microscope. In each of the holes, we put a different substrate. Simple rotation, nothing like this had ever been designed before. We were looking for simplicity. We wanted to build this with only 2 degrees of freedom."	SCI/ENG: "We knew what could be done. The Stanford professor had been working on tip arrays. I had the idea that we could use this array for fresh tips. We knew that (firm A) had moderate voltage piezoelectric motors. Later…we also knew that people were working on lower voltage actuation techniques. More than one group was developing the same novel concept." SCI/ENG: "(The knowledge) was fairly explicit. I went on the website pretty soon to see the actual technology."

APPENDIX A

Factors 4-6 for AFM Design and AFM Tip Array Cases: Quotes and comments

#	Factor	AFM Design	AFM Tip Array
4	Broad personal knowledgebases that are readily searchable	PM: “These microscopes are tools. The problem (is that) of looking at particles. Each of us had different instrument specialties. What drew me in was my expertise with the Scan Probe Microscope (SPM) which includes a specific type of SPM, the Atomic Force Microscope (AFM). Another type of SPM is the Scanning Tunneling Microscope (STM), there are also thermal (microscopes) and others.”	SCI/ENG: “…we have worked with these instruments for awhile and we knew good data when we saw it. We were not using (the AFM) for particles. We were using it for surfaces. (How did you make the leap from surfaces to particles?) Particles are actually a subclass of surface features.”
5	Team and organizational culture encouraging reuse	SCI/ENG: (on relationship between alliance partners) “I was not involved in all aspects of the detailed design. I had to be confident of the abilities of the team to produce the required hardware. In fact an exchange of personnel helped increase confidence. I spent two months at the University of Neuchatel at the beginning of 1999 and (one of their scientists) spent four months at JPL at the end of 1999, beginning of 2000.” SCI/ENG: “… once the relationship was established ...we were mutually reliant on a successful partnership to reach our individual goals...A certain level of trust was necessary to start the joint venture. This trust deepened as the project progressed.”	SCI/ENG: “Very early on (the alliance partner) affirmed that the array concept for tip exchange was a JPL concept and credit for its success would be JPL's…a minimum level of trust, in particular affirmation of the provenance of the concept had to be established early. Successful progress further increased trust of each other.”
6	Personal interest in the technology or science and opportunity to learn in regard to encouragement to reuse.	SCI/ENG: Had been in field for 10 years and was excited about the technology “I was happy to work on this. As much as ‘getting my hands dirty’ with the development of flight hardware, MECA required very well integrated subsystems and I was responsible for maintaining that integration..” PM: Had been working for 10 years in field, was excited about the opportunity and to learn.	SCI/ENG: Had been in the field for 10 years and was excited about the opportunity to develop this technology. However, when the design was complete, he noted “I was quite happy for the U of Neuchatel to handle this.” (hand off the implementation) PM: Had been in the field for 5 years. Although he was excited about the technology, he had more pressing interests and was happy for “someone else” to handle this aspect of the project (hand off implementation)

APPENDIX A

Factors 7 – 9 for AFM Design and AFM Tip Array Cases: Quotes and comments

#	Factor	AFM Design	AFM Tip Array
7	Ability to assess credibility and usability of reusable knowledge	SCI/ENG: "We knew his (potential partner) reputation, and thus, trusted his designs." SCI/ENG: "(need to develop cooperation or interdependence) yes, (initially with European partner team leader and later with team as the project developed.)"	SCI/ENG: "They had results. Very soon after the phone call, I was seeing the pictures on the website. I knew that they had a good reputation. Once I knew they had a system I expected to see a good working model." SCI/ENG: "There are very complex patent issues with piezoresistive sensing. (However) we thought initially, that we could use the piezoresistive units since we did not plan to use it as a commercial product."
8	Ability to assess degree of fit of reusable knowledge to problem	SCI/ENG: "We know that the basic requirements (to operate an) AFM are quite modest. You can run it in air (vs. vacuum) and you don't have to do much preparation. You can get the head compact and good package to fly. We had experience with getting SEM (the other option) qualified for space and it had not been qualified up to now. Thus we saw the benefits of using the AFM over the SEM. (We) thought briefly of the scanning tunneling (microscope, the third option) , but you must have a conducting sample and this type of sample is not expected on Mars."	SCI/ENG: "I talked to (the professor)'s post-graduate student via telephone and he mentioned that they were working on tip arrays. I checked their website for downloadable specifications and pictures of the array. We then invited the professor into a teleconference of the MECA proposal team. I then went up there to meet him while I was seeing other people in the Bay area." SCI/ENG: "Piezoresistive technology did not have the highest resolution, but we knew we could step back from the highest and still fulfill the project needs. Seemed a good match."
9	Ability to assess malleability and implementability of reusable knowledge	PM: "You don't come up with totally new concepts without the idea that you can implement them. We started with manipulation of substrates in a vacuum."	SCI/ENG: "As this aspect of the AFM required the greatest coordination of the hardware and software, we had to have confidence that each party would adhere to mutually agreed specifications, but also be flexible in incorporating any design changes as they became necessary." SCI/ENG: "Scanning with a picture from all the tips simultaneously (as the tip arrays were designed to do) is more difficult than our use of one tip at a time. We didn't know up front that the tips could be removed, but....if you have a tip array there may be details of fabrication that could be modified."

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Factors 1- 3 for Electrometer Design and Lidar Materials Cases: Quotes and comments

#	Factor	Electrometer Design	Lidar
1	Project that is experiencing performance gaps	PM: "Simplistically…you could walk across a carpeted room and get a shock in a cold dry climate. Mars is cold, dry and air is thin, so this is exacerbated. Measurement of the electrical static is known as triboelectric process. Pressure gauge and electrometer may have more in common that other instruments. ..there are a number of ways of measuring pressure in a vacuum . One way is an ion gauge. (It) measures the electrical properties of the gas. Won't work at low vacuum on Mars."	SCI: "The major problem was the cost cap. Full up development would have broken the bank. …(The) key was not the availability of the instrument but the fact that the instrument was in development..." PM: "How do we know a dust devil is approaching and how do we measure it without human intervention." PM: "Packaging (the Lidar) with the camera and shrinking it. (The Canadian partner) had a pre-plan for shrinking it ...and we then developed the packaging with the camera."
2	Risk-reduction requirements	ENG: "(I) contacted (a person at Kennedy Space Center) by phone, and some emails too, then visited his laboratory at Kennedy. I observed his measuring apparatus (it was very large), but had the same operating principles as the one I bought off the shelf. Needed to shrink it from desk top size down to thimble size. (The) instrument was the proof of concept."	SCI: "There was an option to procure an instrument from a sister organization. (This is) a risk management strategy, but funding ramifications would have resulted in the exclusion of certain other instruments from the package. Also, unsure that this would work, as a competing proposal was let out of that center." SCI: "(Due to) Mars disasters last year, (they) have focused attention on risk minimization. (There is) focus on finding a safe landing site during the last phase of dissent. Lidar is a front runner for this use."
3	Personal openness to examine broad set of knowledge to solve problem	PM: "Listed (in the AO) is the general problem of electrostatics. The most intense study is in semiconductor processing or in studying electrical storms. Some knowledge about controlling electrostatics in semiconductor clean rooms. That technology did not answer the fundamental problem. Rubbing things against surfaces you get triboelectricity from friction. Initially interested in what would happen to an astronaut or rover due to electrostatic field...Robot arm generates voltage as it is digging. Cannot measure the voltage in the arm itself, you need an insulating patch. It is very difficult to measure so you must borrow technology from different places." PM (discussing ENG): "I was looking at a single plate and single electrometer like (the ones) we have used for pressure...(the ENG) tries different things to solve problems in sensitive ways. He can be counted on to take an original idea and evolve it to something more sophisticated and capable."	PM: "What is the proper size for an organization. JPL is about as large as you can get so you can do this out of your head (find people with appropriate knowledge). You don't have to know all 5000 people. You seldom have to make more than one phone call to get to the person you need. I conceivably would use an experts directory if there was one, but I would have been more likely to use it 10 years ago. It is easier now to go to (the) web to websites or libraries and look up articles."

APPENDIX A

Factors 4-6 for Electrometer Design and Lidar Cases: Quotes and comments

#	Factor	Electrometer Design	Lidar
4	Broad personal knowledgebases that are readily searchable	ENG: “Electrostatics is a business. (I) went to a conference and took a short course, half day. I didn’t want to reinvent the wheel.” ENG: “(The) connection at Kennedy was important from the standpoint that (the engineer at KSC) was connected to the electrostatic community. As an outsider he introduced me to people who gave freely of their time and suggested improvements.” ENG: “(I) went to a conference in March 1999 at Cambridge...I spoke as an after dinner speaker at the "hot stuff" presentation. They were enthralled. Taylor, the editor of the proceedings asked me to write a paper on electrostatics in MECA.”	PM: “ I recalled that there had been some work here (at JPL) on Laser Range Finding. If you want to do hazard avoidance, you may get terrain mapping using a Lidar. This is pretty wild stuff, manipulating a lander in the landing process without a person (unmanned mission). This is really had for a computer. Laser range finding tells the computer where rocks and hazards are. It might be easier to convert a scanning laser range finder to scan for the dust devils.”
5	Team and organizational culture encouraging reuse	ENG: “There are cultural norms inside NASA to share.” ENG: “I was so far out in front that trust was not an issue. When you develop an instrument, no one can get quickly to that point so you basically have the field to yourself. There are exceptions. When the competition is industrial, they can bring a lot of resources to bear.” ENG: “In the case of the JPL/KSC interaction, we developed a cooperative relationship” (as a byproduct of the reuse experience). ENG: “People in the NASA family are quite generous in knowledge sharing. Outside NASA (they are) more inhibited due to the financial gain involved. I have been quite amazed that you can find out the telephone number of anyone at NASA from the outside...(This) shows a kind of openness that doesn't exist in the outside world.”	SCI: “(There is) some hubris. But it doesn't get in the way of acquiring knowledge...There is a cultural norm of cooperation (compared to) universities (which) are usually competitive.” PM: (is there motivation for reuse and culture of sharing?) “Yes, this place is very unusual in that respect.” (What contributes to knowledge reuse?) “Cafeteria, atmosphere of co-location (and the) cultural norm of cooperation. Universities are usually competitive. Some hubris, but it doesn't get in the way of acquiring knowledge.”
6	Personal interest in the technology or science and opportunity to learn in regard to encouragement to reuse.	ENG: Indicated interest and excitement with project. “I would not do it otherwise. If I (am) not motivated by the challenge, then I should not undertake the task.” … “Learning new things and the challenge of rapid prototyping were the key motivators.” PM: 3 years in field was excited about the technology and the opportunity to learn.	SCI: Was excited about the technology and when asked if he was excited about the project “Very much so. It was my first involvement in a planetary instrument development.” …“I saw this as an opportunity to advance both the technology and my role.”

APPENDIX A

Factors 7 – 9 for Electrometer Design and Lidar Cases: Quotes and comments

#	Factor	Electrometer Design	Lidar
7	Ability to assess credibility and usability of reusable knowledge	ENG: "We actually bought a hand held electrometer…we didn't care about accuracy. Wanted it for hands on experience…we could get the gist of it. We could see what we would be measuring. I could then extrapolate to putting these things in the heel of the robot arm."	PM: "To be quite honest I was happy to take (an scientist at JPL's) word for it. I had confidence in him. We saw the data from the instrument. We met with the Canadian company and they spoke knowledgeably about what we could do with it."
8	Ability to assess degree of fit of reusable knowledge to problem	PM: "…closest thing (to what we needed) is a hybrid between an ion gauge used to measure vacuum in vacuum chambers and cross with a smoke detector." ENG: "(We) talked about putting this (electrometer) on the bottom of the scoop of the robot arm, but it would interfere with the digging as it was too thick. The location was critical. The heel of the scoop was an unused space. (Installation in this location) cuts the volume of the scoop, but this is minimal."	PM: "Of interest was the study of ambient weather patterns...You can't take pictures of everything. You could be on mars and wait for the dust devil to come…(but) how do you get a machine to tell when the dust devil has arrived?…Use a Lidar to tell if a dust devil is arriving and then measure it Isn't this what radar does in an airport? However, radar cannot be used for this (radar has a much longer wavelength and is used for solid objects)...You can now take the person out of the loop. You can now tell the machine to take a picture when the Lidar detects the dust devil in the area."
9	Ability to assess malleability and implementability of reusable knowledge	ENG: "We have a handheld electrometer and you can see the charge from rubbing (it against the material). Basically, I married the two things. (I) mated the rubbed material with the electrometer. As it is rubbed it is automatically measuring. We made the prototype electrometer and insulators. We made six of these things, miniaturized them and located them in the scoop. From there we wnt through a series of prototypes before we got to the flight unit. This stage was useful in component selection and miniaturization."	PM: "Champollion had done the basic conceptual process...shrinking the product from monitor size to the size of a 1 kg. box, and reducing the power. But it was still hard to get this into the project. They told us we could do away with the scanner as they had a camera that could scan. We could put the Lidar in the camera box, (therefore) the camera (would) always (be) looking in the same direction as the scanner. Shrinking the Lidar into a small box camera with two eyes, one was the Lidar."

FIGURE 1
Variance Model

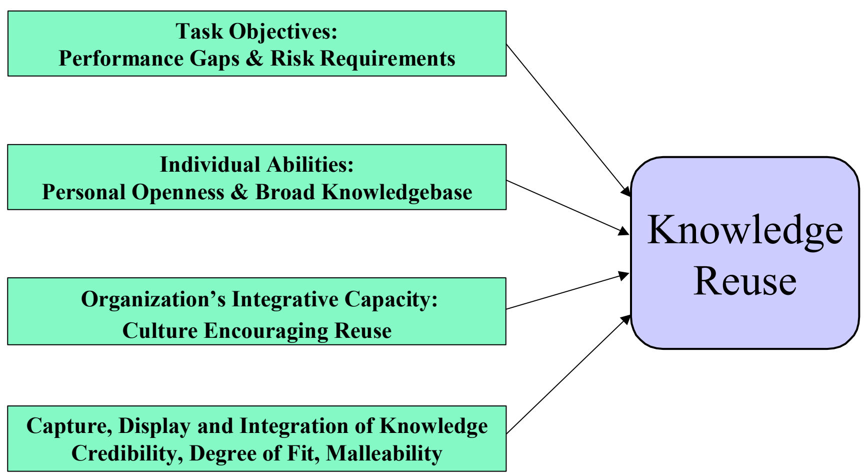

FIGURE 2
Process Model